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Final Report for Grant NAGW-2691: "Magnetospheric Image Unfolding"

INTRODUCTION

The Grant NAGW-2691, "Magnetospheric Image Unfolding" was a three year grant funded under the Space Physics Supporting Research and Technology and Suborbital Program.

Our objective was to develop automated techniques needed to unfold or "invert" global images of the magnetospheric ion populations obtained by the new magnetospheric imaging techniques (ENA, EUV) in anticipation of future missions such as the Magnetospheric Imager and, now, IMAGE. Our focus on the present three year grant is to determine the degree to which such images can quantitatively constrain the global electromagnetic properties of the magnetosphere. In a previous three year grant period we successfully automated a forward modeling inversion algorithm, demonstrated that these inversions are robust in the face of realistic instrumental considerations such as counting statistics and backgrounds, applied error analysis techniques to the extracted parameters using variational procedures, implemented very realistic magnetospheric test images to test the inversion algorithms using the Rice University Magnetospheric Specification Model, and began the process of generating parametric models with the flexibility to handle the realistic magnetospheric images (e.g. Roelof et al, 1992; 1993).

Our plan for the present 3 year grant period was to complete the development of the inversion tools needed to handle realistic magnetospheric images, assess the degree to which global electrodynamics is quantitatively constrained by ENA images of the magnetosphere, and bring the inversion of EUV images up to the maturity that we will have achieved for the ENA imaging.

Below the accomplishments of our three year effort are present followed by a list of our presentations and publications. The accomplishments of all three years are presented here, and thus some of these items appeared on interim progress reports.

ACCOMPLISHMENTS

1) We came to recognize the importance of low altitude imaging, due to our anticipation of the Astrid mission, and we came to recognize that low altitude imaging is much more highly constraining on the global magnetospheric ion distributions than is obvious from casual consideration. On implementing our automated inversion algorithms on images taken from a low altitude perspective, it became vitally clear that the standard exospheric neutral hydrogen density models would not suffice for performing even qualitatively accurate inversions. At low altitudes, all of the major neutral species (H, He, and O) participate in the conversion of H+ to ENA's. What is more, the high variability of these constituents at low altitude (contrary to the character of the high altitude H-atom corona, as discovered by DE-1) became a critical element in the success of the inversion runs. We have therefore incorporated the results of the MSIS-90 thermospheric algorithm, as applied to the relevant dynamic period, into the inversion algorithm procedures, and have demonstrated that step is critical to accurately unfolding the images obtained at low altitude. These results are documented Roelof (1997a). In general, while we have focused on the images created using the Rice MSM model to provide the test images for the development of our inversion techniques (see item 2 below), the true images, such as that returned by Astrid, have become increasingly important as test objects for the development of our procedures, as distinct from their role in magnetospheric science.

2) Parametric models of the magnetospheric ion populations that have the flexibility to accommodate the complexities of the actual magnetospheric parameters are complicated, and they have numerous parameters that are typically not specified in a fashion that insures orthogonality or even robust independence. As we have discovered on implementing our inversion algorithms on the Rice Magnetospheric Specification Model results, it is often the case that the algorithms do not converge because of numerous false minima. Standard minimization procedures, which determine gradients based on vary localized analyses of the χ^2 function, will not always suffice for magnetospheric image inversion. Procedures are needed that examine the χ^2 function in a much more global fashion. We therefore explored a procedure that does just that. The procedure is called the Simultaneous Perturbation Stochastic Approximation (SPSA) which has the additional advantage of requiring far fewer evaluations of

the χ^2 function than do traditional approaches. With this approach, gradients are estimated using a random sampling about the working location in parameter space, allowing the procedure to test the χ^2 function at various distances from that location. As documented in Chin (1998), the SPSA is successful, but not necessarily more efficient than the more sophisticated deterministic methods that we are developing (see below).

3) Our work on inversion has been applied primarily to the problem of Energetic Neutral Atom (ENA) imaging. In principal very similar procedures can be applied to the unfolding of EUV images of the cold plasmasphere. However, there is set of parameters that is much more central to EUV plasmasphere imaging than it is for ENA hot plasma imaging: the position and azimuthal variation of the outer edge of the plasma populations. (A similar problem exists for imaging the magnetopause using ENA imaging). Thus, it was our judgment that there needed to be a special focus on unfolding and characterization of plasma population edges (Our other techniques focus on volume emission properties). We have derived a clever and robust procedure for extracting the 3-dimensional shapes of plasma boundaries (e.g. plasmapause). Imager lines of sight that reveal edges in the emissions are directly mathematically associated with field-line ordered boundaries that can have arbitrary azimuthal structures. The procedure is documented in Roelof et al., (1997b).

4) It is not possible to derive unique "inversions" on the basis of single viewpoint images without the use of substantial constraints on the final solution that are based on our knowledge of the system being imaged. Future missions, such as TWINS, will make use of stereoscopic imaging from multiple spacecraft. However, because magnetospheric imaging involves low optical depth targets, even two views do not allow for unique inversions. The problem is analogous to x-ray tomography in medicine. Since we will never have enough views to perform formal tomographic inversion, it is important to investigate the additional constraints on the image inversions that accrue from the use of multiple views (2-4). We have folded multiple view imaging formally into our image unfolding algorithms and have investigate the additional constraints that such multiple views afford (Roelof et al., 1997b; Skinner and Roelof, 1998).

5) In anticipation of the near-term missions such as IMAGE and TWINS, the practicalities of performing image unfolding processes on

thousands of images from an ongoing mission had to be faced. The algorithms that had been developed were very useful for exploring the limits of magnetospheric imaging. However, the parametric models were still not flexible enough nor robust enough to handle the anticipated variability in true images. We have therefore developed an integrated set of inversion tools for an actual mission that is practicable in terms of the speed of finding a solution and in the robustness of finding the proper solutions irrespective of the starting point of the first guess of the system parameters. Thus, a 32 parameter inversion algorithm was developed that utilizes multiple non-linear minimization techniques (Downhill Simplex, Conjugate Gradient, Hessian Inversion). The procedure automatically switches between these procedures based on analyses of the local conditions of the function that is being minimized. A detailed analysis has been performed of the "end-game" of the searches, where most of the time is traditionally spent, in order to eliminate the very substantial amount of time that is spent in calculations that do not substantially improve the outcome of the procedures. As documented by Skinner and Roelof, 1998, we believe that our algorithm is now suitable for utilization with the detailed images that will be forthcoming from near-term imaging mission.

6) We are in the process of disseminating the understandings and procedures develop during this grant period to the teams involved with the development of the near term magnetospheric imaging (Roelof and Mitchell, 1998a; 1998b). The procedures will become a part of the analysis plans of these missions.

Publications

Barabash, S., P. C:son Brandt, O. Norberg, R. Lundin, E. C. Roelof, C. J. Chase, and B. H. Mauk, Energetic neutral atom imaging by the Astrid microsatellite, Advances in Space Res., 20, 1055, 1997.

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Presentations

(Note: Astrid analyses received partial support from another grant. The procedures developed by work on the present grant played a large role in the analysis of the Astrid data, and there was much cross fertilization between the two efforts).

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Skinner, A. J. and E. C. Roelof, Automated extraction of energetic ion intensities from Energetic Neutral Atom (ENA) images, Eos, Transactions of the American Geophysical Union, 79, S324, 1998.

Educational Outreach

Dr. Chris Chase of our team is mentored a high school student from Centennial High School (Howard County, Maryland), and he utilized the problem of magnetospheric image inversion as the topic of investigation. The student helped in the implementation of the SPSA minimization procedure described previously.

References not in "Publications" or "Presentations" list.

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